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A LABORATORY INVESTIGATION OF WATER HAMMER ASSOCIATED WITH THE ESTABLISHMENT OF FLOW IN A PIPELINE CONTAINING CENTRIFUGAL PUMPS

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Charles Samuel Martin

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SUMMARY

Field observations of extremely large transient pressures in a pipeline containing centrifugal pumps led to the study of such a system in the laboratory. The pipeline in the field was used for transporting a slurry, and the pressure fluctuations apparently were associated with temporary clogging of the pipe. The laboratory pipeline, which contained centrifugal pumps in series and a valve at the upstream end, duplicated the essential features of the system in the field. The purpose of the laboratory investigation was to determine the source, and thus the cause, of the pressure fluctuations that followed the sudden opening of the valve.

Pressure-time records were obtained at three stations (one downstream from each pump) by means of pressure transducers and electronic recording equipment. A partial analysis of these records led to the conclusion that the first major pressure waves (water hammer) originated in the pumps. Since preliminary measurements of the pressure differences across the pumps, as well as noise, indicated that there was severe cavitation in the pumps prior to the opening of the valve, it was concluded that the first pressure waves resulted from the collapse of vapor cavities in the pumps. The implosions occurred at the upstream pump, the middle pump, and the downstream pump, consistently in that order.

The origins of three other waves were not ascertained. More complete analysis of the data was prevented primarily by two factors. First,

definite knowledge of whether such pressure disturbances are transmitted, reflected, absorbed, or "broken up" by a pump was not at hand, and the data themselves were inconclusive in this respect. Second, the recording equipment was not well suited to the system. The frequency response of the recorder (oscillograph) was somewhat low, and a much more responsive instrument (an oscilloscope) revealed that the diaphragm of the pressure transducer apparently vibrated in resonance with wave reflections in the branch leading to the transducer. Therefore, details of form of the pressure-time records are not believed to be accurate, nor are the indicated magnitudes of the peak pressures. However, it was concluded that the recorded times of the major pressure pulses were essentially correct. The time relationships of the major pressure pulses recorded at the various piezometers were the basis of the analysis.

When a pipeline which is under low overall pressure becomes blocked at a point upstream from a pump, cavitation in the pump may become severe. The primary value of this study is the evidence that water hammer may result from the collapse of the cavity in the pump when the obstruction is suddenly removed.

CHAPTER I

INTRODUCTION

Definition of the Problem.--Despite the remarkably complete work of Allievi (1) on water hammer in pipelines, much remains to be discovered regarding the origins of elastic waves in closed systems, especially in pipelines containing centrifugal pumps. One area in particular in which a minimum of research has been conducted is that of water hammer resulting from large-scale cavitation in the centrifugal pumps themselves. This aspect of the study of water hammer is the subject of the laboratory investigation reported herein.

Water hammer is the somewhat misleading name given to the extreme pressure fluctuations which result when a liquid flowing in a closed conduit is decelerated rapidly. Deceleration requires a rise in pressure downstream; if the deceleration is sufficiently abrupt, the increased pressure is great enough to compress the fluid. An abrupt pressure rise creates an elastic-wave front, or density discontinuity, which is propagated through the fluid at the acoustic velocity and which continues to travel, being reflected at reservoirs and dead ends, until finally the disturbance is damped out through viscous resistance. Conceivably, elastic waves can be associated with acceleration as well as deceleration of the flow, but in the usual practical circumstances only decelerations involve velocity changes abrupt enough to create elastic waves in liquids.

Commonly, water hammer is visualized only in the pipe system upstream from a valve that is rapidly closed. However, there are other circumstances which lead to water hammer. The rapid closure of a valve leads also to low pressure on its downstream side. With a fixed pressure at the distant downstream end of the pipe, the inertia of the liquid may be great enough that the pressure on the downstream side of the valve is reduced to the saturation vapor pressure before the motion is arrested. If a vapor cavity of appreciable size is formed, "column separation" of the liquid is said to occur. Following separation, the return flow causes a collapse of the cavity, or a rejoining of the liquid column, and the sudden deceleration inherent in the collapse of the cavity is sufficient to cause water hammer.

Water hammer has also been known to occur in a pipeline near a centrifugal pump, following an electric power failure. The sequence of events is similar to what takes place downstream from a rapidly closed valve. In this case, when the energy supply is suddenly removed, the pressure in the pipeline downstream from the pump falls rapidly. The inertia of the liquid downstream may contribute to the lowering of the pressure to the extent that column separation occurs.

Another example of water hammer has been observed in the transportation of slurries through pipelines. In one such case, centrifugal pumps in a pipeline used to transport a phosphate slurry literally exploded under apparently normal conditions of operation. Studies led to the hypothesis that sudden clogging of the pipeline created a sequence of events quite similar to those downstream from a suddenly closed valve.

The likelihood of column separation at the blocked area is enhanced if it occurs where the pressure is normally low, as on the suction side of a pump.

A further possibility for water hammer exists in pipelines containing centrifugal pumps when the pipe becomes clogged and remains blocked long enough for a steady state corresponding to zero flow to become established. If the pressure downstream from a pump is not large, the pressure in the eye of the impeller may be low enough for a vapor cavity to form. A sudden unclogging of the pipeline can then result in the collapse of the cavity. The implosion causes water hammer.

The writer's investigation was conceived from the practical problem encountered in the slurry system. A model of such a system was constructed. It consisted of a pipeline with three centrifugal pumps in series. The pumps were made to cavitate with zero flow, duplicating probable conditions in a clogged slurry-transportation system. Then the rapid opening of a valve at the upstream end of the pipeline represented the sudden unclogging of the pipeline.

Previous research of an exploratory nature had been conducted by Professor M. R. Carstens of the Georgia Institute of Technology. Professor Carstens investigated water hammer in the same system used for the writer's investigation, but he was interested only in detecting the presence of water hammer, and not in studying the pressure fluctuations in detail. His purpose was to show that large pressure fluctuations, probably water hammer, were present, hypothesizing that they followed the collapse of vapor cavities in the centrifugal pumps. Thus, the writer's investigation was an extension of this exploratory study.

Objective and Scope of the Present Investigation.--The study of water hammer in pipelines described herein was an experimental investigation. The purpose was to reveal the history of the pressure disturbances that resulted when a valve at the upstream end of a pipeline was suddenly opened. The pipeline contained three centrifugal pumps in series, and the operation of the valve was intended to represent the sudden unclogging of the pipeline. The principal objective was to detect the origins of water hammer, and thus to reveal whether or not cavitation in the pumps led to water hammer. Column separation, as a cause, was presumably eliminated because a steady state with zero flow was established to begin with.

Review of the Literature.--Some of the earliest experiments concerning water hammer were American studies, such as those of E. B. Weston (2) and S. B. Russell (3). None of the early American experimental investigations, all conducted before 1900, were of great value, as no theory was developed which could be used with confidence. Thus, the classical work by N. Joukovsky (4), who gave an analytical explanation of the phenomenon of water hammer and verified it experimentally, was of a pioneering nature.

Joukovsky developed formulas describing the magnitude and speed of propagation of a pressure wave following instantaneous closure of a valve in a water conduit. He corroborated his mathematical analysis by experiment. Joukovsky showed that the maximum amplitude of a pressure wave caused by the complete stoppage of flow in a conduit was ρcV, in which ρ is the mass density of the liquid, c is the celerity of sound in the liquid medium, and V is the mean velocity of flow prior to closure. He also included the effect of elasticity of the conduit walls in his analysis. The resulting expression for the celerity, c, of a pressure wave in a circular conduit is

$$c = \sqrt{\frac{E_L/\rho}{1 + \frac{E_L D}{E_c \delta}}} \qquad (1)$$

in which

E_L is the bulk modulus of elasticity of the liquid,

E_c is the modulus of elasticity of the conduit material,

D is the inside diameter of the conduit, and

δ is the thickness of the conduit wall.

Shortly after Joukovsky developed his theory, L. Allievi (1) contributed a theory on the unsteady motion of water in closed conduits. Allievi made a mathematical analysis of the maximum pressure resulting from the gradual closure of a valve. He also studied resonant conditions of water hammer in conduits. Although similar in many respects, Allievi's studies were more extensive than those of Joukovsky in that he considered more than instantaneous closure.

An American engineer, N. R. Gibson (5), developed independently of Allievi a detailed theory of water hammer which gave identical results. Gibson showed how the increase of pressure caused by the gradual closure of hydraulic turbine gates may be determined from Joukovsky's theory. He included the effect of wall elasticity in providing a trial-and-error method of arithmetic integration for the determination of pressure fluctuations in a penstock.

Joukovsky's, Allievi's, and Gibson's theories are all restricted in scope to the pressure fluctuations in a pipe upstream from a suddenly closed valve. None of their works concerns the pressure disturbances resulting from column separation at the downstream side of a suddenly closed valve. Column separation apparently has not been the subject of any theoretical analysis, but it has been the object of some recent experimental investigations.

C. J. Apelt (6) performed tests on field pipelines containing centrifugal pumps, discovering that when the pipeline profile was irregular and the pressure head was low, column separation was possible following pump shutdown. He verified experimentally that the elastic-column theory of water hammer, as described by Joukovsky and Allievi, was applicable as long as column separation was not present. Apelt established beyond doubt that each independent column of water after separation behaved as described by the elastic-column theory, which requires a continuous liquid. He noted that the study of water hammer following column separation has been virtually untouched in the field of basic research.

A similar investigation on pumps was conducted by R. J. Richards (7). Richards investigated column separation in existing pump discharge lines by conducting field tests. He measured the pressure at various locations along the pipelines after the pumps were shut down purposely. The water hammer which he observed apparently originated from the rejoining of water columns previously separated at points of low pressure. Richards concluded that one could not by analytical means determine the maximum pressure rise caused by column separation.

E. A. Bunt (8) studied experimentally the pressure fluctuations which followed the rapid closure of a valve at an intermediate location in a pipeline. He studied transient conditions on both sides of the valve. However, recognizing that phenomena upstream from the valve had been studied extensively, he devoted most of his attention to the study of the formation and collapse of vapor cavities on the downstream side of the valve. Bunt discovered, by means of photographs, that large vapor pockets formed, and later collapsed, on the downstream side of the valve immediately after sudden closure. He also discovered that pressure fluctuations of water hammer intensity occurred upon the return of the separated water column to the valve.

The present investigation is similar to the three mentioned above in that it was concerned with water hammer that apparently is caused by the collapse of large vapor cavities. Evidence is presented once more that water hammer can be present in situations other than those associated with the sudden stoppage of flow at the downstream end of a conduit. It is hoped that this investigation will be helpful to future investigators who are interested in similar problems.

CHAPTER II

INSTRUMENTATION AND EQUIPMENT

General.--The laboratory tests in this investigation were conducted in the Hydraulics Laboratory, School of Civil Engineering, Georgia Institute of Technology. The arrangement of the test equipment is shown in Figure 1. The equipment consisted of three centrifugal pumps connected in series by copper tubing. As shown in Figure 1, the pumps and piping were submerged in a tank filled with water to prevent the leakage of air into the system at points where the pressure was less than atmospheric. The electric motors were placed outside the tank.

Preliminary to the water hammer tests, two series of steady-flow tests were conducted for the purpose of obtaining characteristics of the pipeline and the pumps. These characteristics were used in the later analysis of the water hammer tests. The two series of steady-flow tests are referred to as series 1 and series 2. Series 1 was conducted for the purpose of obtaining a relationship between the energy gradient in the pipe and the discharge. The purpose of series 2 was to obtain performance characteristics of the pumps, specifically, the relationship between the flow rate and the pressure difference across the pumps with the discharge control valve at the upstream end, as in the water hammer tests.

Pumps and Piping.--Each pump was a bronze Oberdorfer Model 1G-P, and was driven by a 1/3-horsepower split-phase electric motor. The pumps were operated at 5000 revolutions per minute by means of belts and pulleys.

The pipeline consisted of 1/2-inch ID copper tubing, and was arranged in coils to occupy a small space. The exact lengths of pipe are shown in Figure 2. A globe valve at the downstream end of the pipeline was used to regulate the discharge during series 1. The rate of flow during series 2 and the water hammer tests was regulated by a plug valve installed at the pipeline inlet. A scale (shown in Figure 1) was constructed in order that the exact position of the handle could be known during the tests. The scale was divided into nine equal divisions. At position 9 the valve was closed; at position 0 the valve was open.

Steady-Flow Instrumentation.--Piezometers were located at various positions along the pipeline. The exact position of each piezometer is shown in Figure 2. The piezometers consisted of 1/2-inch ID copper tubes of variable length. The tubes at piezometers 1, 2, 4, 5, 7, and 8 were 36 inches long, while those at piezometers 3, 6, and 9 were nine inches long. At the end of each piezometer tube a needle valve was attached in order that the pressure from the pipeline could be transmitted to the pressure measuring equipment. Figure 3 illustrates how buckets of water were used to submerge the valves in order to prevent leakage of air into the system. A flexible plastic tube led from each valve to a Bourdon gage. The gage was calibrated to 0.1 psi for positive pressures and 0.1 inch of mercury for negative pressures. The piezometer tubes and the Bourdon gage are shown in Figure 3.

In series 1, the discharge was measured by means of a weighing tank and an electric timer. The water temperature was obtained for determining the specific weight and the viscosity.

Unsteady-Flow Instrumentation.--During the water hammer tests, Statham Laboratories pressure transducers were used to record the transient pressures. The transducers were located at the ends of the tubes at piezometers 3, 6, and 9. Two transducers are shown encased in plastic wrapping in the upper portion of Figure 4. Their natural frequency was slightly less than 4000 cycles per second when their diaphragms were in contact with water.

Oscillographs.--Two Sanborn oscillograph recorders were used to record the transient pressure signals from the transducers. One oscillograph was equipped with two channels and the other with one. Each channel was supplied with an amplifier that contained all the essential equipment necessary to amplify and balance the signal from the respective pressure transducer. The oscillographs were capable of following a transient signal up to a frequency of 100 cycles per second. They were equipped with a marking device which made a mark on the recording paper (oscillogram) each second during operation. They were also equipped with a timing device by which all records could be synchronized. An oscillograph is shown in Figure 5.

Oscilloscope.--An oscilloscope was used to supplement the pressure-time record at piezometer 3 obtained from the oscillograph. The oscilloscope was used for the purpose of attempting to reproduce the results obtained with the oscillographs. Because the frequency response of the oscilloscope was much greater than that of the oscillograph, it was expected that a more exact history of the pressure waves would be obtained. Thus, it was hoped that any part of the transient condition that was not recorded by the oscillographs would be recorded by the more responsive oscilloscope. The oscilloscope, a DuMont cathode-ray type, is shown in Figure 6 with a camera attached for recording the pressure history at the piezometer.

CHAPTER III

EXPERIMENTAL PROCEDURE

Steady-Flow Tests.--The purpose of conducting the steady-flow tests was to obtain the resistance characteristics of the pipeline and the performance characteristics of the pumps. These characteristics were needed in the analysis of the data from the water hammer tests.

Series 1 was performed to obtain a relationship between the energy gradient in the pipe and the flow rate. All tests were conducted in the Blasius range of Reynolds numbers (the maximum Reynolds number was approximately 2×10^5). Therefore, the slope of the energy line, S, can be expressed as

$$S = KG^{1.75} \tag{2}$$

in which

$$K = \frac{0.316}{(\frac{\pi}{4})^{1.75}\ 2g^{1.75}}\ \frac{\mu^{0.25}}{\gamma^2 d^{4.75}} \tag{3}$$

In these equations, G is the weight rate of flow in lb/sec, μ is the dynamic viscosity in lb-sec/ft^2, γ is the specific weight in lb/ft^3, and d is the inside diameter of the pipe in ft. Measuring the value of d directly with sufficient accuracy for computing K by equation (3) was not considered possible. Therefore, K was determined by experiment, through simultaneous measurements of S and G and the use of equation (2). Enough tests were performed to insure that K was well defined. The data from series 1 are listed in Table 1, and the results--values of K--are given in Table 2. Some additional data on the shut-off head of each pump were obtained in series 1 and are tabulated in Table 1.

Series 2 was conducted for the purpose of obtaining performance characteristics of the pumps for various inlet-valve positions. The pressure at piezometers 1, 2, 4, 5, 7, 8, and 9 was measured during the tests, and, with K known, the discharge was computed from equation (2). Pressure measurements were conducted for 11 different inlet-valve positions with all three pumps running. The data from these tests are listed in Table 3, and the relationship between the inlet-valve position and the discharge is shown in Figure 7. In Figure 8 is shown the performance characteristics of the pumps, and in Figure 9 are shown the pressure grade lines for various inlet-valve positions.

Water Hammer Tests with the Oscillographs.--Four tests were conducted with the pressure transducers connected at piezometers 3, 6, and 9. These tests were designated as runs A, B, C, and D. All three pumps were operating during these tests. Electrical signals from the pressure transducers were transmitted to the oscillographs.

Before the water hammer tests were begun, each oscillograph was calibrated. A change of pressure of 50 psi was imposed on the transducers by means of compressed air from the laboratory supply. A constant pressure was maintained by means of a pressure regulator. The pressure was measured by means of a Bourdon gage while the deflection on each oscillogram was noted.

The water hammer tests were begun by letting all three pumps run until a steady state of flow was reached. Then the inlet valve was closed by moving the operating handle to position 9. Since all pumps remained running, very low pressures resulted on the suction side of each pump, as indicated in Figure 9. The valve was left in position 9 for 10 or 15 seconds in order that a new steady state (zero flow) could become established. Then the inlet valve was rapidly opened to position 2 (maximum flow) by releasing a spring. Pressure-time records were obtained on the oscillograms for all water hammer tests. Typical records are shown in Figure 10 and Figure 11. All four runs were conducted similarly.

Water Hammer Tests with the Oscilloscope and Camera.--With the exception that a different method was used to record the history of the shock waves, these tests were conducted in a similar manner. A camera was used to photograph the pressure-time record on the oscilloscope.

Through the use of various sweep speeds of the electron beam across the oscilloscope screen, the time scale of the pressure-time record could be expanded or contracted. Tests were conducted at various sweep speeds and many camera shutter speeds. The test procedure used was identical to that used during the tests with the oscillographs. A pressure calibration was obtained through identification of two corresponding pairs of known steady-flow conditions on the oscilloscope and on Figure 9, namely, zero discharge (valve position 9) at the beginning of each run and maximum discharge (valve position 2) at the end of each run. The steady-state pressures for these two inlet-valve positions could be obtained from the results of series 2. Thus a pressure-time record at piezometer 3 was obtained.

CHAPTER IV

ANALYSIS AND DISCUSSION OF RESULTS

Steady-Flow Tests.--The purpose of the steady-flow tests was to obtain the relationships shown in Figures 7, 8, and 9. These figures show certain characteristics of the system which were significant in the analysis of the water hammer tests.

Figure 7 is a calibration curve for the control valve at the pipeline inlet, which was used in the series 2 tests and the water hammer tests. Figure 8 shows the performance characteristics of the pumps. Figure 9 shows the pressure grade lines in the pipeline for various positions of the control valve at the inlet.

A noteworthy feature of Figure 7 is the marked decrease in the flow rate that occurred when the inlet-valve was closed beyond position 4 (moved from position 4 to position 9). It is believed that this is partially attributable to cavitation in the pumps. The discontinuity in the curve was introduced with the belief that the cavitating and non-cavitating conditions should be represented by different functions. Further evidence of cavitation in the pumps is seen in Figure 8.

Two different operating conditions are represented by the pump performance curves in Figure 8. The three curves at the top (open circles) were obtained in series 1 with the discharge-control valve located at the downstream end of the pipeline and, consequently, with positive pressure throughout the pipeline. These curves are typical of non-cavitating pumps. The three curves at the bottom (blacked-in circles) were obtained in series 2 with all three pumps operating and with the control valve at the upstream end of the pipeline. Negative pressures are expected with zero flow in such a system, especially if the downstream end of the pipeline is not deeply submerged and if the system contains several pumps in series.

The pressure grade line in Figure 9 for valve position 9 (zero flow) illustrates the low pressures to be expected in the upstream portion of such a system. With zero flow in this system, the minimum pressure in the pipeline was -12.9 psig, or 1.2 psia,* occurring upstream from pump 1. Lower pressure yet is expected at the center of the vortex in the eye of the impeller of pump 1. Apparently, cavitation in pump 1 was so severe that no pressure rise was observed across it. Therefore, the suction pressure at pump 2 was also -12.9 psig. Apparently, also, slightly less severe cavitation occurred in pump 2 and still less in pump 3, resulting in the increasing magnitudes of the pressure rise (Δp) across these pumps. These increasing magnitudes of Δp are seen also in Figure 8. That the pumps were cavitating at zero flow is pertinent to the analysis of the water hammer tests because the inlet valve was closed at the beginning of these tests.

Unsteady-Flow Tests.--Figures 10 and 11 are oscillograph records from one of the runs in the water hammer tests. They are typical of all the

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*The saturation vapor pressure of the water (80°F) was 0.5 psia. The minimum atmospheric pressure on the day in question, obtained from U. S. Weather Bureau records, was 14.1 psia.

runs. Figure 10 is a graph of pressure versus time at piezometer 3. Figure 11 is a graph of pressure versus time at piezometers 6 and 9. Parts of the oscillograph records are not visible in the reproductions (Figures 10 and 11), but they were visible on the original records. These parts of the oscillograms were heavied up, and clear reproductions are provided in Figures 10A and 11A. The tick marks that permitted the synchronization of the records during each run were necessary for comparing Figures 10A and 11A. The relative times of occurrence and the magnitudes of the pressure pulses were measured on the oscillograms by means of a microscope micrometer; these measurements are listed in Table 4. In the analysis of Figures 10A and 11A, the results of series 2 (namely Table 3 or Figure 9) were needed for obtaining the steady-flow pressures at valve positions 2 and 9.

Figure 12 is a simplified re-drawing of Figures 10A and 11A. It is intended to clarify the time relationship of the pressure pulses recorded at piezometers 3, 6, and 9. The time scale has been expanded to make the relative times of occurrence of the pressure waves at the different piezometers more clearly discernible. In Figure 12, each pressure pulse has been given a number, with the same number assigned to the pulses at different piezometers in cases where it is believed that the pulses were caused by the passage of the same wave. Thus the numbers are also identification numbers for the various waves. Figure 12 represents one of the four test runs. However, the same pattern was observed in every run.

By means of Figures 10A, 11A, and 12, a limited analysis of the history of the pressure disturbance (water hammer) may be attempted.

The analysis leads to plausible suggestions regarding the origins of the pressure waves. An important basis of the analysis is that vapor cavities existed in the pumps prior to the sudden opening of the inlet valve. This was established in the preceding discussion of the steady-flow tests. In Figure 12, it appears that there were six significant pressure waves during each run; there were four at piezometer 3, five at piezometer 6, and one at piezometer 9. Wave 1 appeared only at piezometer 3. The first pulse at the next piezometer (piezometer 6) is thought to be a different wave because the time interval between it and the first pulse (wave 1) at piezometer 3 is much greater than the time required for wave 1 to travel from piezometer 3 to piezometer 6.

It was determined from series 2 that the lowest pressure in the pipeline occurred at both sides of pump 1 (see Figure 9). Furthermore, immediately after the rapid opening of the inlet valve, the pressures in the pipeline on the suction sides of pumps 2 and 3 were less than atmospheric (see Figure 9), while the pressure on the suction side of pump 1 was slightly greater than atmospheric. Therefore, since at the instant the valve was opened the pressures in the eyes of all three pumps were nearly equal (see Table 3), it is plausible that the atmospheric pressure at the inlet (near the suction side of pump 1) as contrasted with subatmospheric pressures on the suction sides of pumps 2 and 3, caused the higher pressure to reach pump 1 first. Thus, it is believed that wave 1 was caused by the collapse of a vapor cavity in pump 1.

It appears from Figures 10A and 11A that piezometers 6 and 9 did not receive the impulse from wave 1. Evidently, wave 1 did not pass pump 2. It may have been absorbed in pump 2, or it may have been reflected at pump 2. In any case, it is concluded that no subsequent pulse at any of the piezometers was caused by wave 1 because of the time lapse (a time scale is furnished in Figure 12).

Wave 2 was indicated at piezometer 6 only, and there is no complete explanation of its origin. It seems unlikely that wave 2 resulted from a first collapse of a vapor pocket existing in pump 2 because it was not recorded at the other side of pump 2, that is, at piezometer 3.

Wave 3 was indicated at practically the same instant at piezometers 3 and 6. From Figure 2 it is noticed that piezometers 3 and 6 are nearly equidistant from pump 2. Hence, it is believed that wave 3 emanated from the collapse of a vapor pocket in pump 2. Moreover, since no large pressure fluctuation appears in the pressure-time record for piezometer 9 at the proper time, apparently wave 3 did not pass pump 3.

A similar conclusion may be drawn regarding wave 4, as it was recorded at two locations, piezometers 6 and 9, at practically the same instant. It is noted that piezometer 3 indicated a pressure only slightly above normal steady conditions at the instant wave 4 was recorded on piezometers 6 and 9. This is an indication that no large pressure fluctuation went past pump 2. Also, wave 4 was recorded at piezometers 6 and 9 at practically the same instant, providing a basis for the same conclusion that was drawn regarding wave 3, that is, wave 4 is believed to have originated with the collapse of a vapor pocket in pump 3.

It is thus presumed that waves 1, 3, and 4 were the result of three separate implosions, one at each pump. Each wave is believed to have been a result of the collapse of a cavitation pocket formed in the pump when the pipeline was blocked at a point upstream from the pumps.

No plausible explanation is given concerning the origin of waves 5 and 6. It is noted that wave 5 passed piezometer 3 before it reached piezometer 6, and the time lag corresponds to that computed by dividing the distance between the piezometers by the celerity of the pressure wave. Similarly, wave 6 appears to have traveled from piezometer 6 to piezometer 3, but its origin also is uncertain. It appears either that a wave passed a pump or that pulse 5 (and also pulse 6) was actually two waves whose times of appearance at two successive piezometers coincided with the travel time between the piezometers.

In summary, the data are indicative that implosions of vapor cavities occurred at pumps 1, 2, and 3 in that order (waves 1, 3, and 4). Other pressure pulses were recorded. One pulse (number 2) was recorded between pumps 2 and 3 only. A pair of pulses was recorded at piezometers 3 and 6 so as to indicate that another wave (number 5) may have traveled from the discharge side of pump 1 to the suction side of pump 3. Still another pair of pulses indicated similarly that a wave (number 6) may have traveled from the suction side of pump 3 to the discharge side of pump 1. It is thought that the data were too meagre to permit tracing waves 2, 5, and 6 to their origins.

<u>Analysis of Oscilloscope Records</u>.--As mentioned previously, the purpose of the measurements with the oscilloscope was to supplement the pressure-time records obtained from the oscillographs. Since the frequency response of the Sanborn oscillograph is known to be less than 100 cycles per second (cps), pressure fluctuations with frequencies much greater than 100 cps would not be faithfully recorded. Therefore, measurements

of the pressure history at piezometer 3 were made with the more responsive oscilloscope as a check on the accuracy of the oscillogram.

Figures 13b, 13c, and 13d are pictures of the pressure-time record at piezometer 3 of waves 1, 3, 5, and 6. Figure 13a is a picture of wave 1 only. It is evident from Figures 13b, 13c, and 13d that four waves were present, as seen previously on the oscillogram. It is noted that the pressure-time records obtained from the oscilloscope and the oscillograph are similar in pattern. However, there are indications of impossibly large negative pressures on the oscilloscope record (wave 1) that do not appear on the oscillogram. This portion of the record is believed to be an indication of excessive displacement of the transducer diaphragm, caused by resonance.

The hazy portion in Figure 13a, which corresponds to the passage of wave 1 at piezometer 3, indicates a very high frequency of oscillation of the transducer diaphragm (3360 cps). It was learned from the manufacturer that the natural frequency of the pressure transducers when filled with water was slightly less than 4000 cps. As these two frequencies are about the same, it is possible that resonance occurred. Apparently, the indications of impossible pressures on the oscilloscope were, instead, indications of excessive displacement of the transducer diaphragm which resulted from the near equality of the imposed frequency and the natural frequency of the transducer.

In summary, the indicated magnitudes of the pressure pulses on the oscilloscope records evidently are meaningless because the frequency of reflections of pressure waves in the tube between the transducer and the piezometer connection coincided with the natural frequency of the transducer. However, the general agreement in the pressure-time patterns that were indicated on the oscilloscope and on the oscillogram encourages confidence that sufficient detail was obtained by means of the Sanborn oscillograph. Evidently, the oscillograph was too unresponsive to detect the unwanted resonance in the piezometer tube.

CHAPTER V

CONCLUSIONS

Inferences drawn from the investigation are not as complete as desired because, as the analysis of the data proceeded, it became apparent that pressure measurements at other points were needed for positive identification of each pressure wave. Moreover, because the investigation was basically an exploratory study of a specific system, the conclusions are not entirely general. Nevertheless, the following observations were made:

1. A small-scale pipeline, connecting two reservoirs and containing three centrifugal pumps in series, was constructed in the laboratory for the purpose of studying extreme pressure fluctuations during the brief period of unsteady flow immediately after the abrupt opening of a valve at the upstream end of the pipeline.
2. Severe cavitation in the pumps while the valve was closed was noted. Three characteristics of the system contributed to the low overall system pressure which resulted in the cavitation. The pipeline was only slightly below the water surface in the reservoir. The closed valve was at the upstream end of the pipeline. The pipeline contained several pumps in series.
3. Pressure pulses of high intensity were detected at all three piezometers. The pulses appeared to have been due to the passage of pressure waves (water hammer) in the pipeline.

4. Three of the pressure waves appear to have originated with implosions in the pumps, occurring at the upstream pump, the middle pump, and the downstream pump in that order. The data are indicative that the implosions were due to the collapse of the vapor cavities in the cavitating pumps, following the sudden opening of the valve. The origins of the other waves were not established. Whether they resulted from other implosions or whether they were reflections could not be ascertained. Nevertheless, the collapse of vapor cavities in the pumps was established as the first cause of the extreme pressure fluctuations.
5. The reproducibility of the pressure-time records from one test run to another is indicative of a consistent cause-effect relationship that is characteristics of the system. Although the conclusion that cavitation in the pumps is the original cause of the water hammer is therefore limited to the system studied, it is reasonable that similar circumstances in other systems produce similar results.
6. The time relationships of the major pressure pulses at the respective piezometers, which are the basis of the analysis, are considered essentially correct. However, the values of peak pressure intensities, as well as details of the pressure-time records, are not quite correct because (1) the frequency response of the oscillograph was too low to record faithfully much detail and (2) reflections of pressure waves in the branch connecting the transducer and the main pipe apparently occurred with a frequency about equal to the resonant frequency of the instrument. This emphasizes the care that must attend the choice of a pressure-measuring technique for transients.

7. Whether a pressure wave is transmitted, absorbed, or reflected by an operating centrifugal pump, whether or not its intensity and form are changed, and what relationship may exist between the degree of cavitation in a pump and these changes in the wave are questions for which answers were not found in the data. In fact, *a priori* knowledge of this sort would have aided the present analysis. Answers to these questions should be sought in studies of simpler systems.

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APPENDIX

Table 1. Data from Series 1 Tests

Pressure at Pipe Center-line for Various Operating Combinations of the Pumps

Pumps Operating	Gage Pressure in psi									Flow Rate (G) in lb/sec
	Piezometer Number									
	1	2	3	4	5	6	7	8	9	
1, 2, and 3	-2.1	18.9	11.5	3.5	24.7	17.4	8.9	31.8	22.8	0.660
1 and 2	-1.2	21.0	16.0	10.5	33.2	28.1	22.4	21.0	14.9	0.532
1	-0.4	23.0	20.2	17.3	16.7	13.9	10.8	10.1	6.9	0.377
1	0.4	27.0	-	-	-	-	-	-	-	0
2	-	-	-	0.3	26.6	-	-	-	-	0
3	-	-	-	-	-	-	0.3	28.3	-	0

Note: The last three operating conditions tabulated in Table 1 were tests for determining the shut-off head of each pump.

Table 2. Results from Series 1 Tests

Values of $K = S/G^{1.75}$

Pumps Operating	Flow Rate (G) in lb/sec	K
1, 2, and 3	0.660	0.878
1 and 2	0.532	0.875
1	0.377	0.871

Table 3. Data from Series 2 Tests

Pressure at Pipe Center-line for Various Positions of the Discharge-Control Valve

Valve Position	Gage Pressure in psi							Flow Rate (G) in lb/sec
	Piezometer Number							
	1	2	4	5	7	8	9	
0	-4.9	16.8	-2.5	19.6	-1.0	21.8	10.4	0.765
1	-1.6	19.7	-0.6	21.3	0.3	22.5	10.8	0.777
2	-0.9	20.1	-0.1	21.8	0.5	22.7	10.9	0.780
3	-2.1	18.9	-1.1	20.8	0	22.2	10.7	0.774
4	-6.3	14.8	-3.8	18.1	-1.4	21.0	10.2	0.743
$4\frac{1}{2}$	-10.4	9.7	-6.7	13.5	-3.6	17.9	8.8	0.648
5	-11.6	-0.3	-10.7	3.8	-6.5	11.6	5.5	0.526
$5\frac{1}{2}$	-12.4	-5.1	-11.2	-1.4	-8.0	6.7	3.5	0.385
6	-12.8	-8.8	-11.9	-4.5	-8.1	3.8	1.8	0.278
7	-12.1	-11.4	-12.1	-6.5	-6.7	1.3	0.8	0.102
* 8	-12.1	-12.1	-12.7	-7.7	-9.2	0.9	0.6	--
9	-12.9	-12.9	-12.9	-12.1	-12.1	0.6	0.6	0

* Pulsating flow was present at this valve position.

Note: Series 2 was conducted with all three pumps operating.

Table 4. Data from the Oscillograms

Time of Occurrence in Seconds Referenced from Wave 1 and the Magnitude in psig of Each Wave for Each Run

	Piezometer 3		Piezometer 6		Piezometer 9	
Wave	Time (sec)	Magnitude (psig)	Time (sec)	Magnitude (psig)	Time (sec)	Magnitude (psig)
			Run A			
1	0	75	-	-	-	-
2	-	-	0.360	31	-	-
3	0.449	140	0.458	236	-	-
4	-	-	0.591	258	0.591	220
5	0.693	73	0.705	158	-	-
6	1.140	43	1.128	41	1.198	21
			Run B			
1	0	57	-	-	-	-
2	-	-	0.430	31.5	-	-
3	0.485	138	0.484	226	-	-
4	-	-	0.621	260	0.624	207
5	0.724	74	0.735	172	-	-
6	1.158	239	1.123	40	1.263	19
			Run C			
1	0	64	-	-	-	-
2	-	-	0.390	31.5	-	-
3	0.470	154	0.469	226	-	-
4	-	-	0.589	260	0.589	228
5	0.672	64	0.695	132	-	-
6	1.115	37	1.097	41	1.169	21
			Run D			
1	0	62	-	-	-	-
2	-	-	0.410	40	-	-
3	0.487	148	0.486	230	-	-
4	-	-	0.607	260	0.617	213
5	0.717	75	0.730	142	-	-
6	1.152	42	1.141	40	1.206	21

Figure 1. Arrangement of Laboratory Equipment.

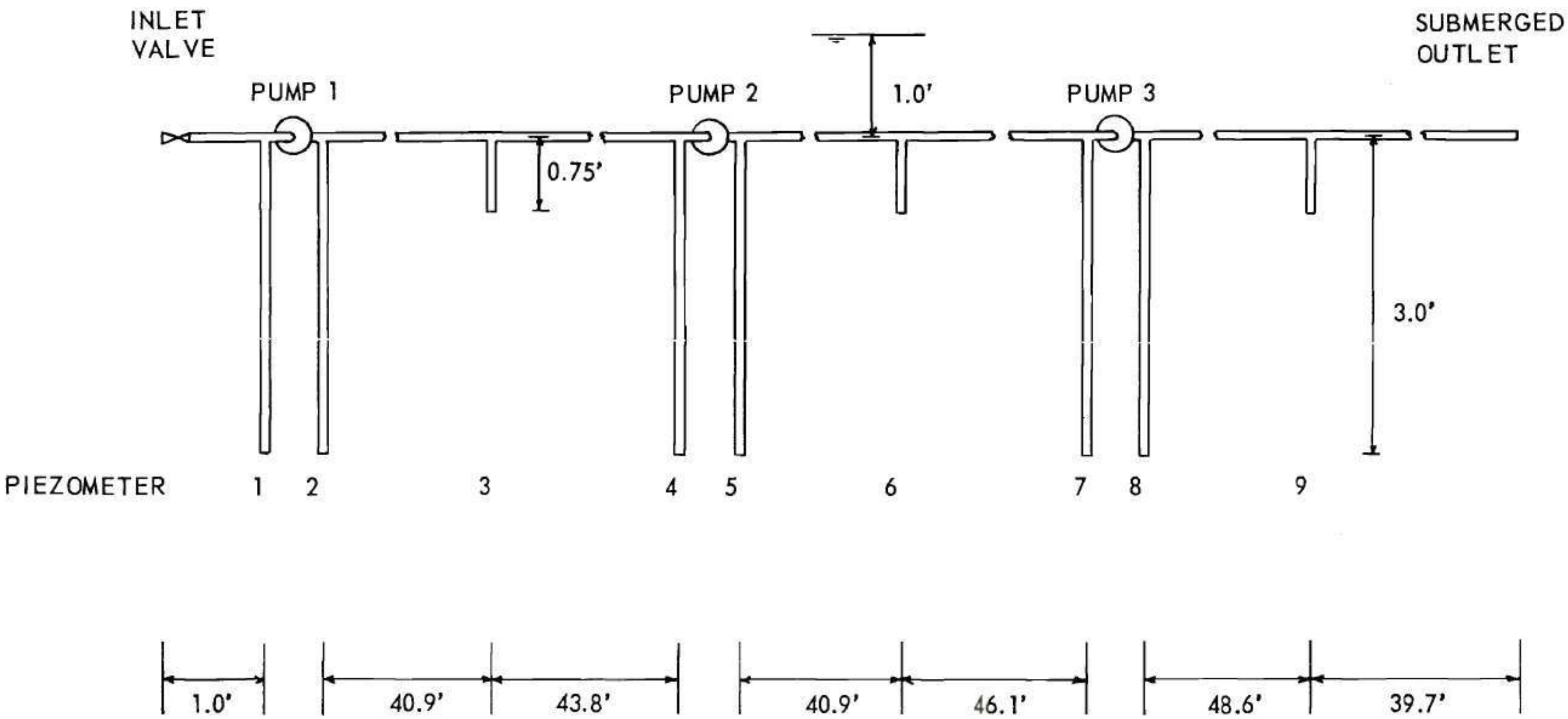


Figure 2. Location of Piezometers.

Figure 3. View of Steady-Flow Pressure Measuring Equipment.

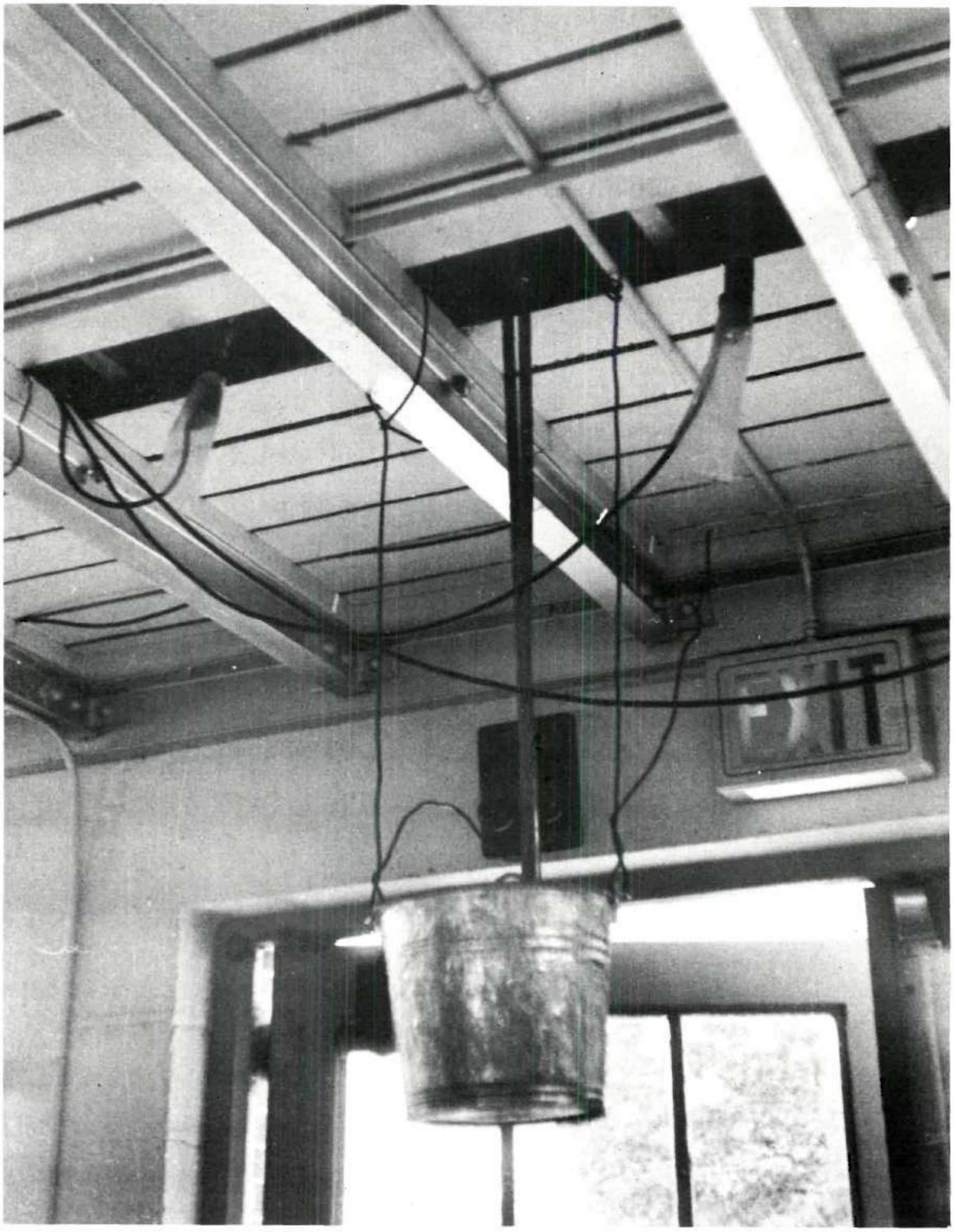


Figure 4. View of Pressure Transducers.

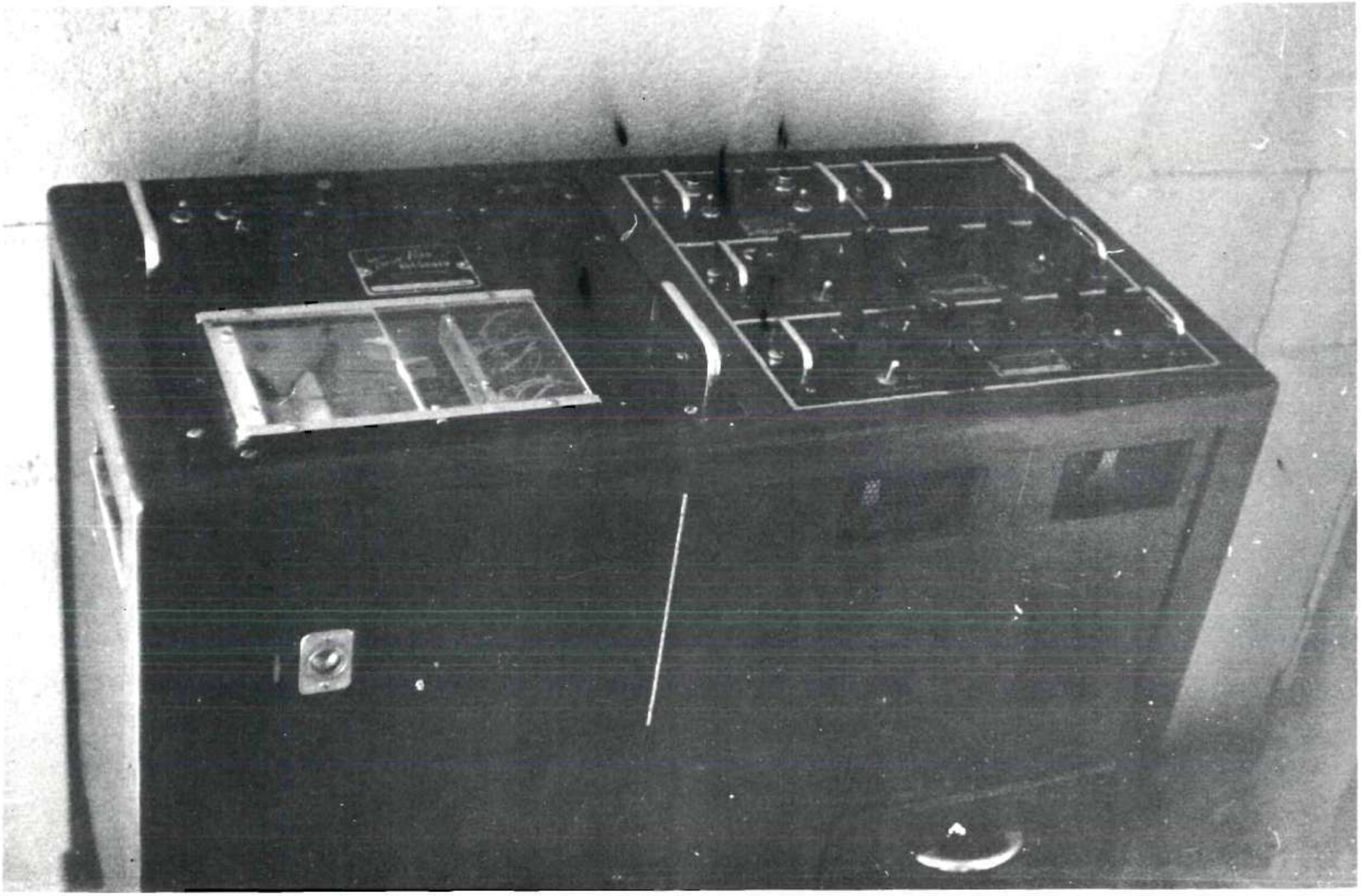


Figure 5. View of Typical Oscillograph.

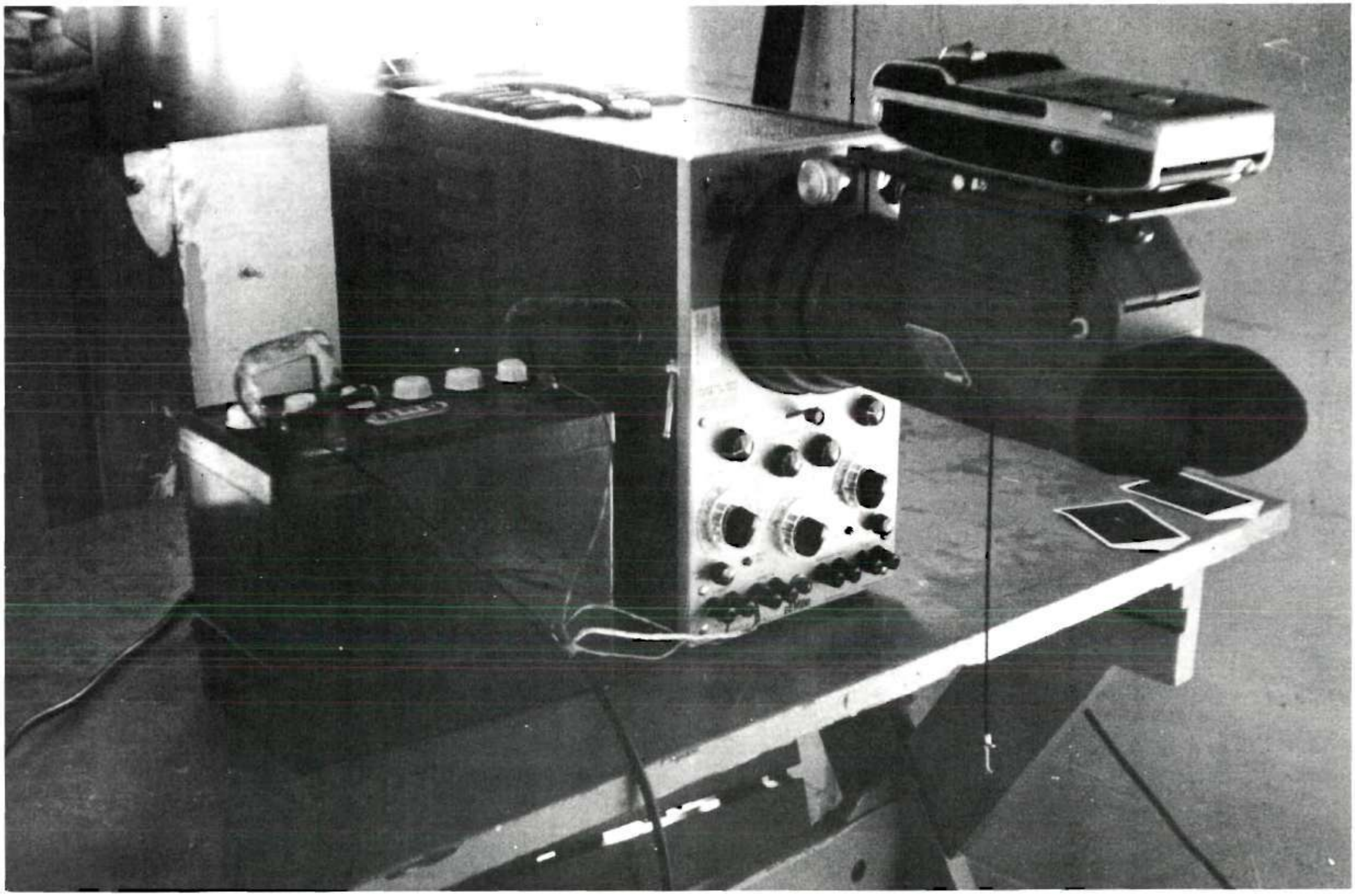


Figure 6. View of Oscilloscope and Camera.

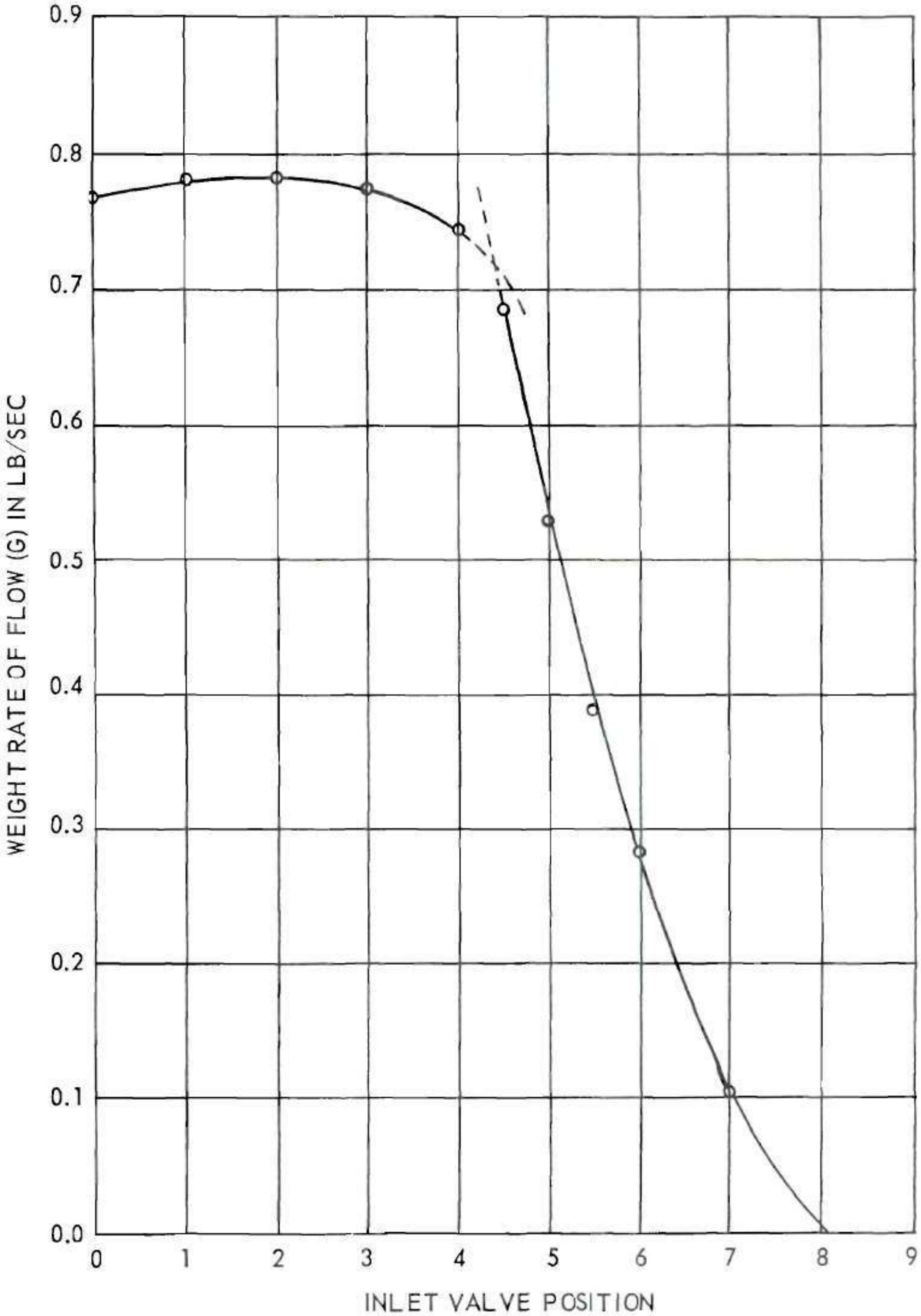


Figure 7. Calibration of Inlet Valve.

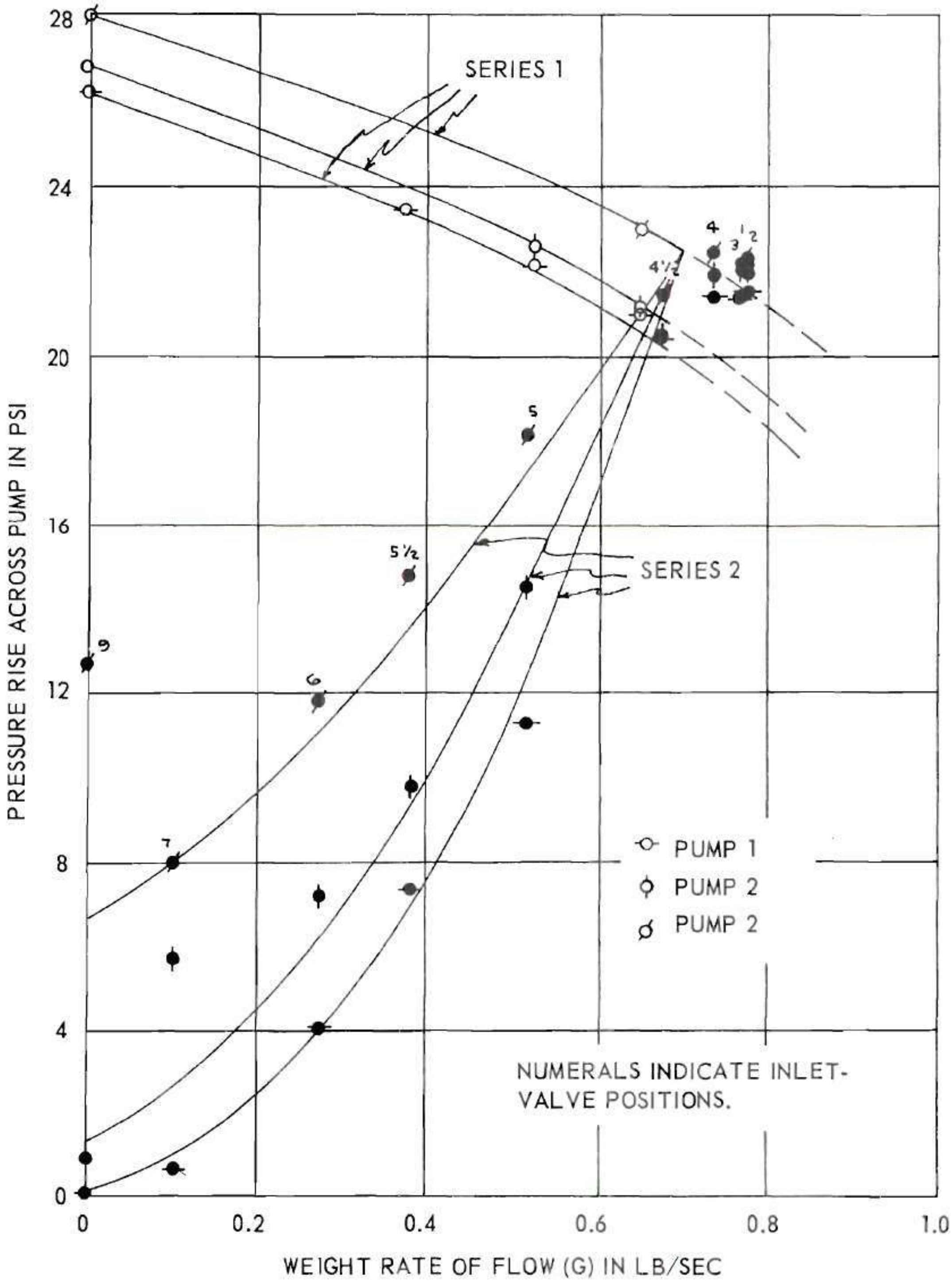


Figure 8. Performance Characteristics of the Pumps (3 Pumps in Series).

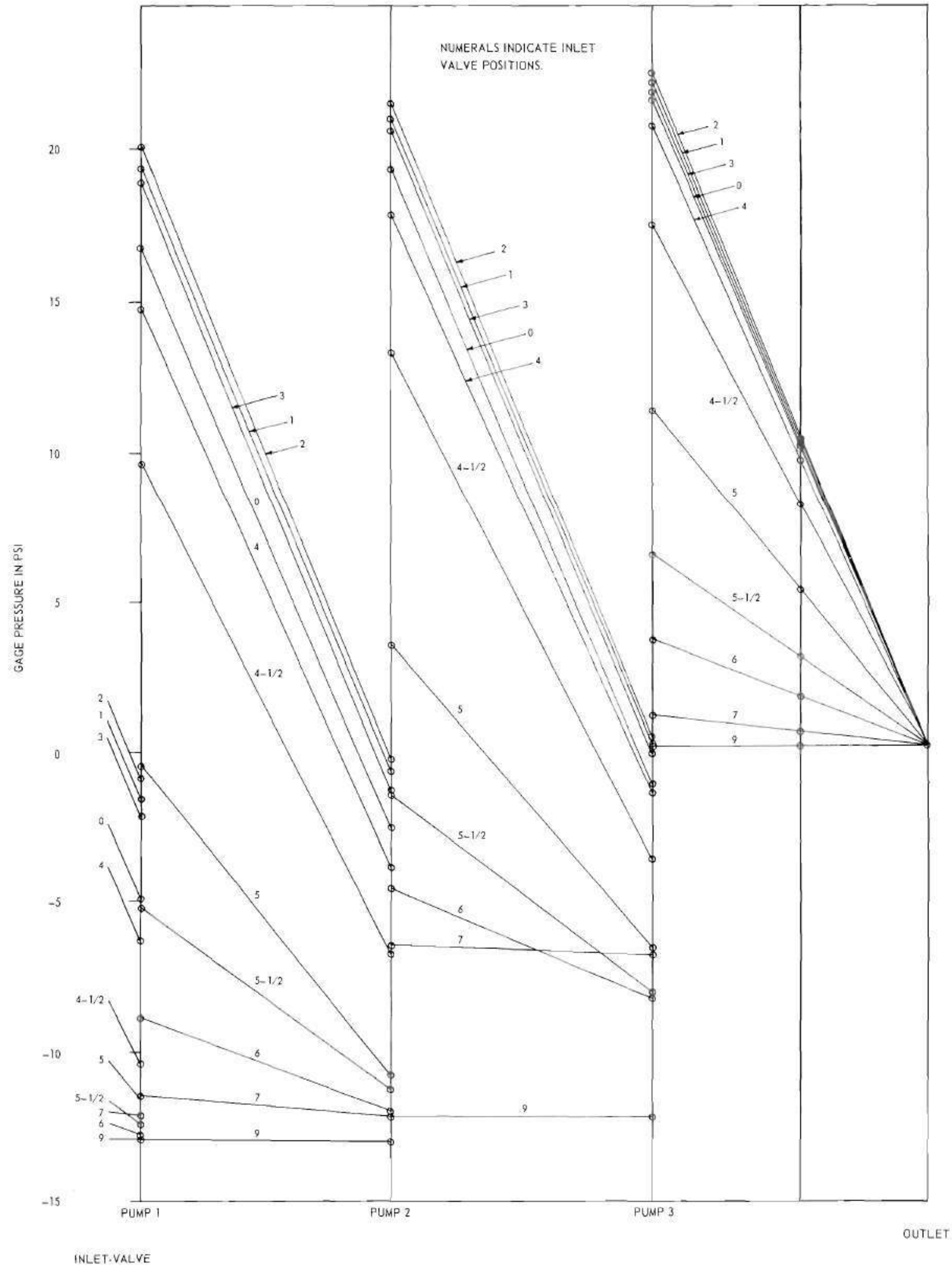


Figure 9. Pressure Grade Lines in Piping.

Pressure-time record at piezometer 3.

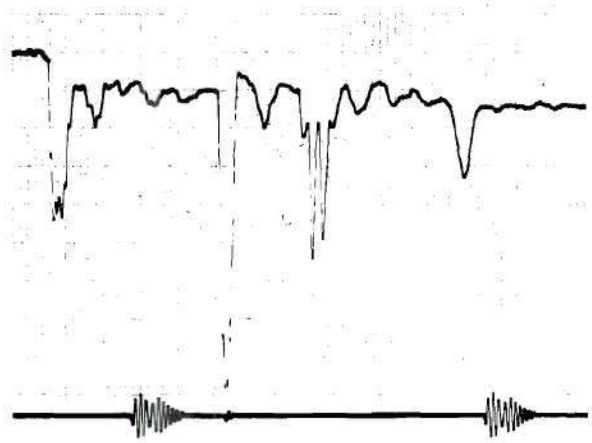


Figure 10.

Pressure-time record at piezometer 9.

Pressure-time record at piezometer 6.

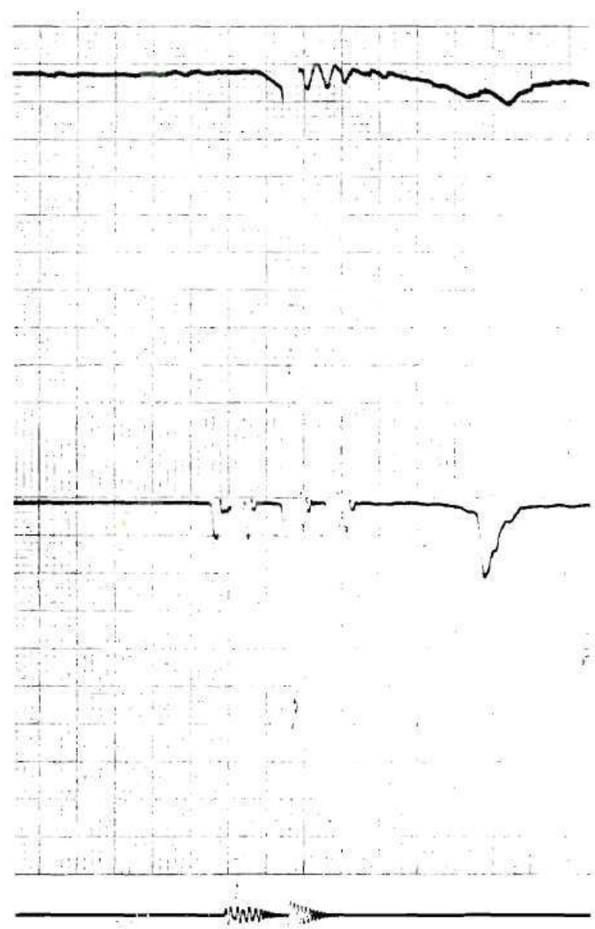
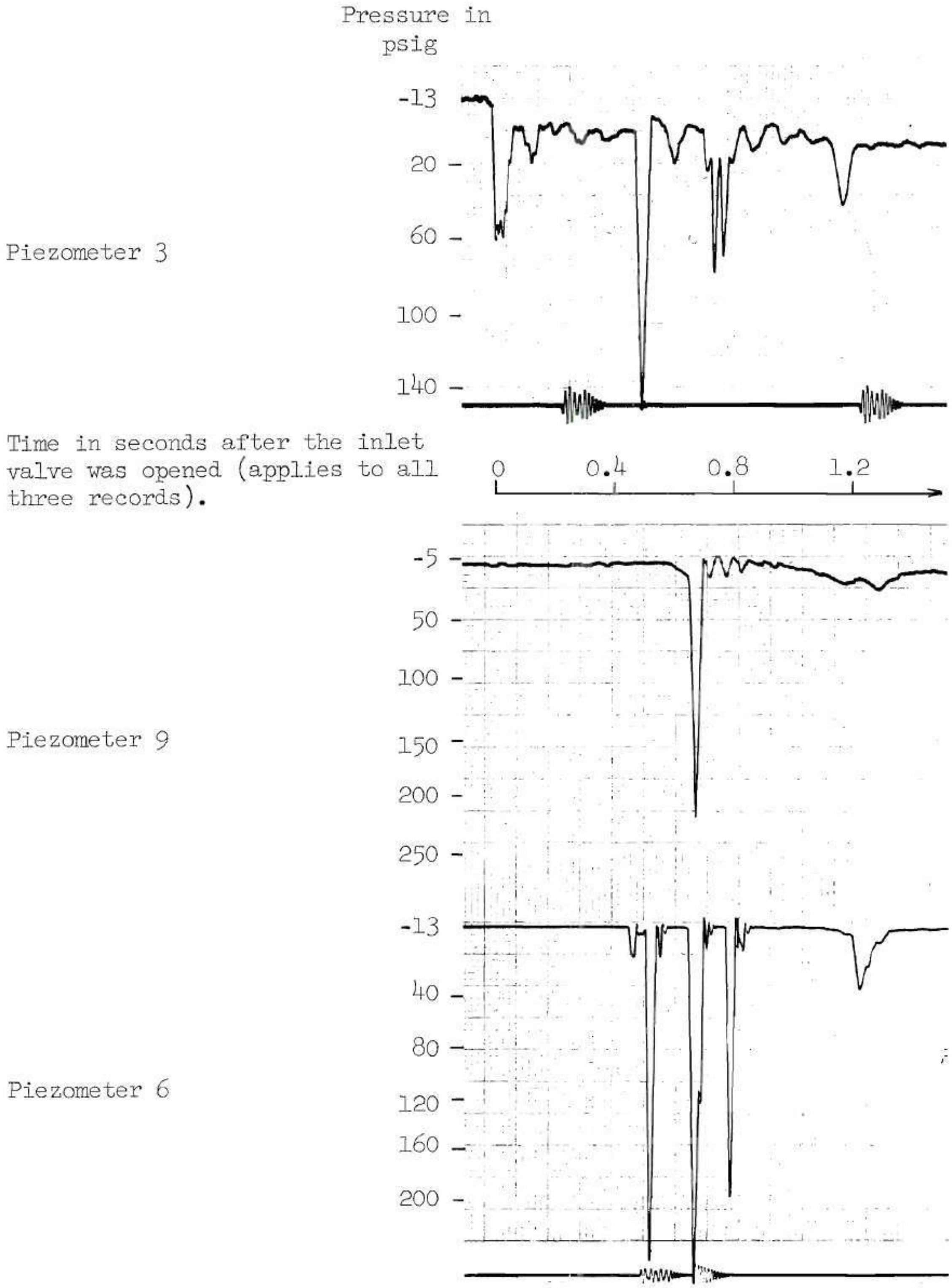


Figure 11.

Figures 10 and 11. Original Oscillograph Records.



Figures 10A and 11A. Modified Oscillograph Records.

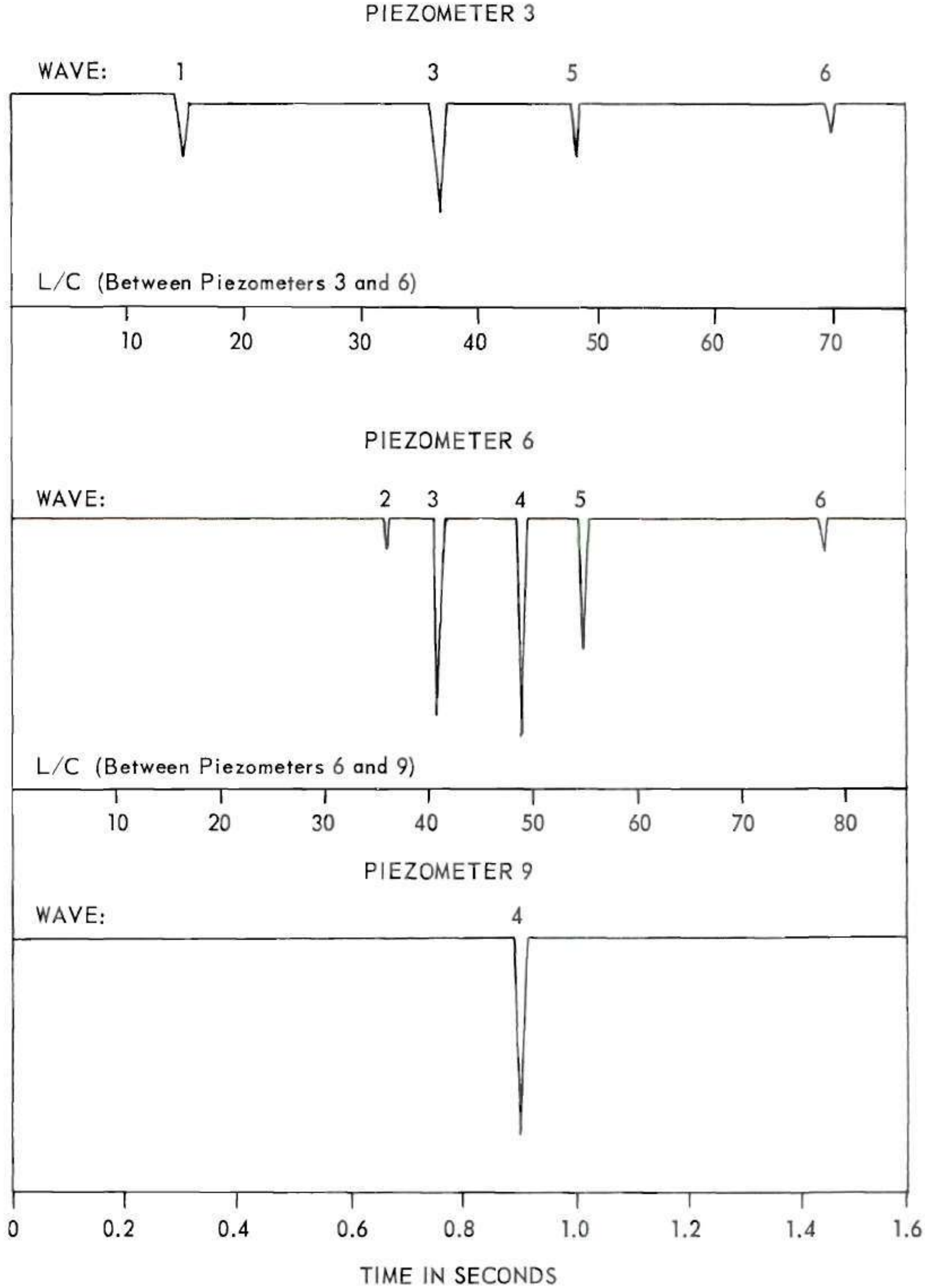
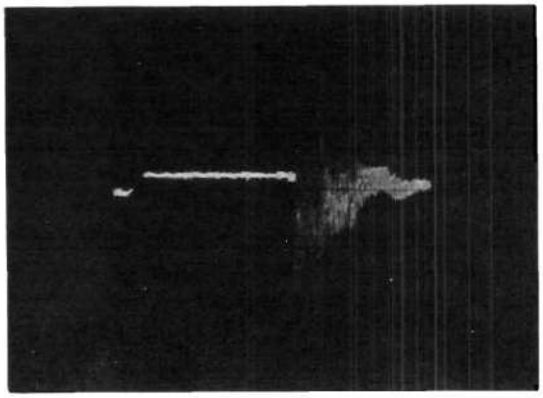
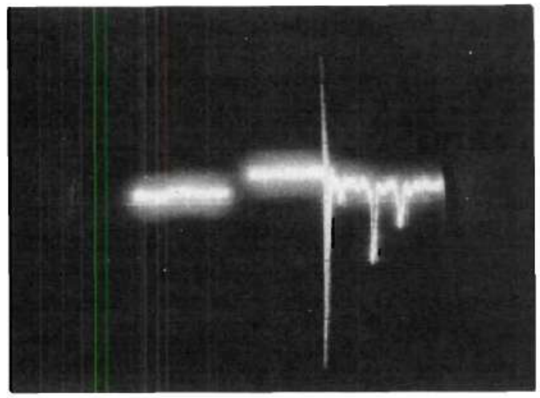


Figure 12. Schematic Drawing Showing Pressure Against Average Time Characteristic of Each Run.



0.2 sec.

a.) Wave 1 only.

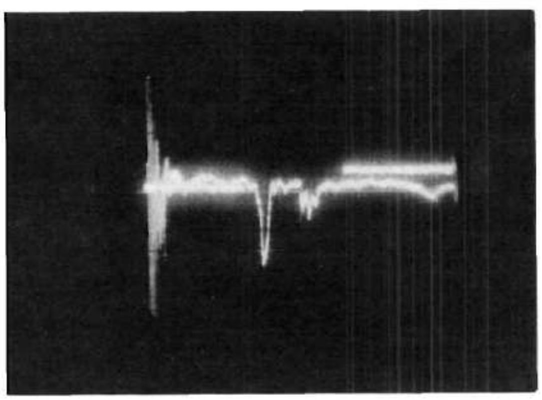


2.0 sec.

b.) Waves 1, 3, 5, and 6.

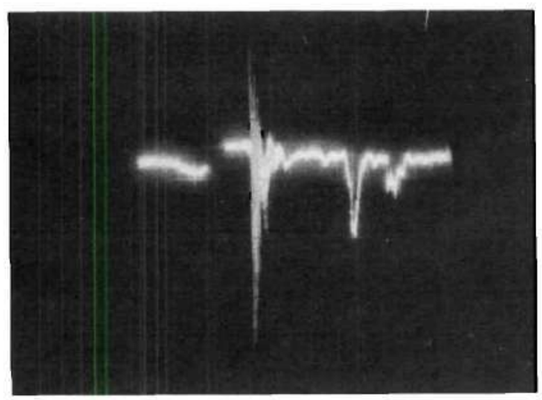
Time

Pressure



1.0 sec.

c.) Waves 1, 3, 5, and 6.



1.0 sec.

d.) Waves 1, 3, 5, and 6.

Pressure scale: 0 psi – 200 psi

Figure 13. Oscilloscope Records at Piezometer 3.